LA-UR -88-1738

CONF-880410--2

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--88-1738

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TITLE: THE FOG-OIL ANOMALY CONFIRMED IN HELSMK-I TESTS

AUTHOR(S): SIG GERSTL, T-DOT
SHIRISH CHITANVIS, T-DOT
ANDREW ZARDECKI, T-DOT
JAMES WALLACE, FAR FIELD, INC., SUDBURY, MA
FRED GEBHARDT, SAIC, LEXINGTON, MA
BOB DEKINDER, PM/SMOKE/OBSCURANTS, U.S. ARMY

SUBMITTED TO: PROCEEDINGS OF THE SMOKE/OBSCURANTS SYMPOSIUM XII, HELD AT THE JOHNS HOPKINS UNIVERSITY, LAUREL, MD, 4/19-21/88

MAY 1988

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

The Fog-Oil Anomaly Confirmed in HELSMK-I Tests.

Sig Gerstl, Shirish Chitanvis and Andrew Zardecki
Los Alamos National Laboratory, Los Alamos, NM 87545
and
James Wallace
Far Field Inc., Sudbury MA.
Fred Gebhardt
SAIC, Lexington, MA.
Bob Dekinder
PM/Smoke/Obscurants, U.S. Army.

ABSTRACT.

Modeling analyses of preliminary experimental data obtained from the High Energy Laser (HEL) beam propagation tests (HELSMK-I) through tactically significant smokes are presented for the case of Fog-oil (FO). Thermal imager data together with transmission measurements and other experimental evidence are used to reconstruct and model the interaction physics of the HEL beam with FO. An earlier theoretical model by Wallace (1983) predicted that the high energy beam would vaporize large (>10μm) FO droplets, while the smaller droplets primarily conduct their energy to the ambient air, thereby enhancing thermal blooming in air. This behavior is categorized as an anomaly for the interaction of a HEL beam with aerosols because complete vaporization would normally have been expected.
The HELSMK-I test together with computational results from our nonlinear beam propagation codes confirmed this prediction. Fog-oil can thus be classified as an effective smoke shield against a HEL threat in open air at infra-red wavelengths, at flux levels of a few tens of Kilowatts/cm^2. These results also validated our computer models which show that a punch-through effect is prevented in FO due to its enhanced blooming characteristics.

1. INTRODUCTION.

The purpose of the HELSMK-I test was to investigate the efficiency of various obscurants in blocking a high energy laser beam generated by the MIRACL laser (wavelength $\lambda = 3.8$ μm). The flux level of the beam upon focusing was around 40 kW/cm^2. Our aim was to model the interaction of this high energy laser beam with obscurants such as Fogoil (FO) in order to understand and predict its blocking properties.

The propagation of a HEL beam through obscurants is characterized by two types of effects. (a) Linear: beam spread due to scattering from the obscurants and turbulence, and absorption due to air molecules and the dispersed aerosols. (b) Nonlinear: aerosol vaporization, ionization (plasma formation), non-linear optical effects such as Stimulated Raman Scattering and Stimulated Brillouin Scattering in droplets, and last but not least, thermal blooming in air.

In this paper we shall argue that at the flux levels provided by the MIRACL laser, larger FO droplets vaporize, whereas the smaller ones simply conduct heat to the atmosphere, thereby enhancing atmospheric thermal blooming.

2. SUMMARY OF HELSMK-I TEST RESULTS.

The experimental setup is sketched in Fig 1 and described in detail by Farmer and Dekinder (1986). Basically, the HEL beam (at 3.8 μm) was focused roughly in the center

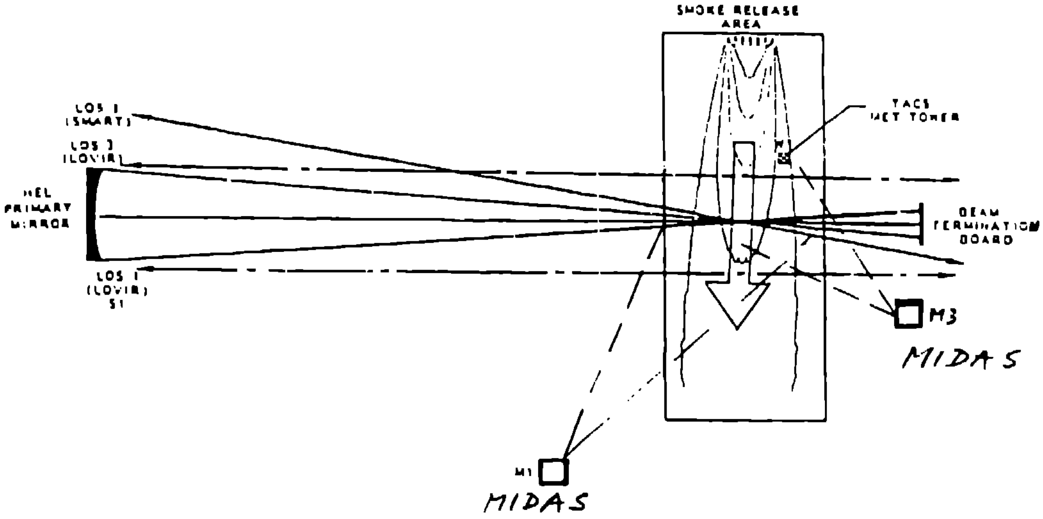

Figure 1. HELSMK-I experimental setup. The HEL laser beam travels from left to right, and focuses roughly in the middle of the the smoke release area. For details, refer to Farmer and DeKinder (1986).

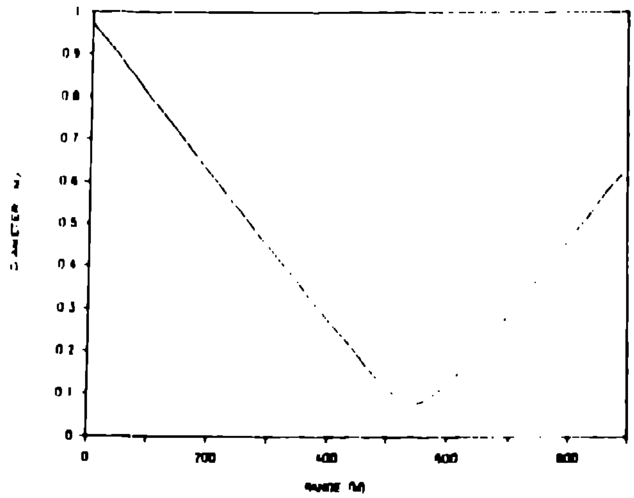

Figure 2. Ray optics calculation of the diameter of the beam as it traverses to the target board

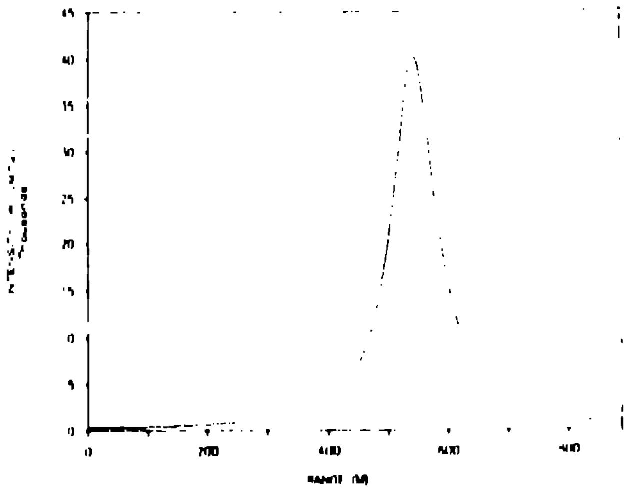

Figure 3. Calculation of the HEL intensity as a function of the propagation distance, assuming 1MW beam power

of the smoke release area (see Fig 2). The beam flux level reached a peak level of roughly 40kW/cm^2 at the focus (see Fig. 3). The beam diameter at the focus was approximately 10cm (see Fig 2). The following diagnostics were obtained

1) HEL energy deposition on target board

2) Low power transmissometers along and across the HEL beam

3) Thermal imagers (MIDAS) in the 3-5μm and the 8-12μm range

4) Smoke data, such as particle size and concentration were measured

The beam wander was negligible. The cross-wind was between 0.8 and 4 m/s during the duration of the test. The beam shape is roughly C-shaped.

HEL shots were made in clear air and FO. The clear air shots melted the Aluminum target plate. All FO smoke shots left the target plate intact, implying that the FO-smoke attenuates the HEL beam. Thus there was no punch-through effect, whereas one expected, in view of the low latent heat of FO that it would be completely vaporized. This is the so-called FO anomaly.

The other puzzle was that whereas the diameter of the beam was of the order of a few tens of cms in the smoke release area, the thermal imager data (at 8-12μm) showed the presence of a hot-spot roughly 10m in diameter. This was the so-called hot-spot puzzle.

3. THE FOGOIL ANOMALY.

Despite the low latent heat of FO (1/10 that of water), measurements have shown that the vapor pressure around fogoil droplets is extremely low . This is due to the high effective molecular weight (approximately 275) of FO (Gebhardt and Turner (1980) Since the vapor pressure is low, the FO droplets have to be heated up to its boiling temperature (approximately 627°K) before they will start to vaporize. This "non-vaporization" effect is quantified by several codes: LASER (at LANL), NONLIN (Wallace), ABVPRO (Gebhardt).

The non-vaporizing effect is particularly true of small (submicron to micron size) FO particles, when conduction to the atmosphere dominates vaporization of the FO droplet (see Fig. 4, which encapsulates results from the code LASER). In this case, it is possible

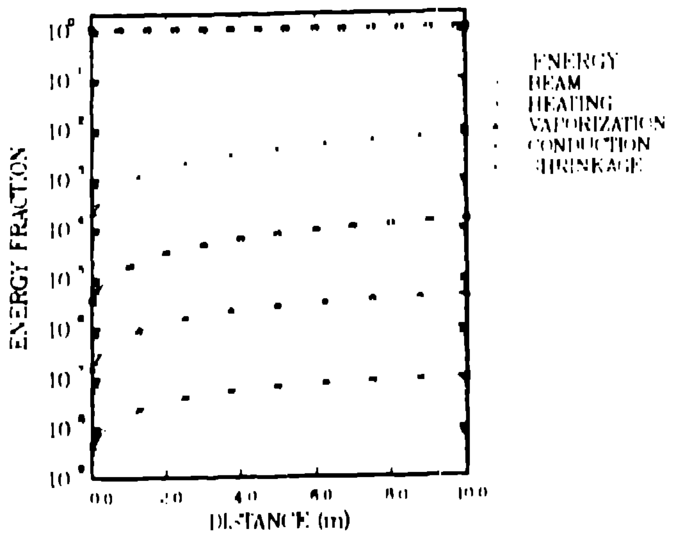

Figure 4. A computation of the energy fraction lost to various mechanisms along the propagation path through FO. Notice that conductive losses of heat to the ambient air dominate the vaporization process for this case

to get an analytic result for the temperature rise of the droplet (Armstrong et al (1985)):

$$\Delta T = \frac{aQF}{4\kappa}\left(1-\exp\left(-\frac{t}{t_{cond}}\right)\right) \qquad (3.1)$$

where ΔT is the temperature rise of the droplet, a is the radius of the droplet, Q_a is the Mie absorption efficiency of the droplet, F is flux level, κ is the thermal conductivity of the droplet, and t_{cond} is the characteristic thermal conductivity time scale given by $\rho C_v a^2/3\kappa$. This time scale is of the order of sub-microseconds, so that the asymptotic value given by setting t to infinity in Eqn.(3.1) is achieved quickly. For a = 1.0 µm, ΔT = 340 C for F = 10kW/cm^2. This compares well with the results of the code NONLIN (see Fig. 5).

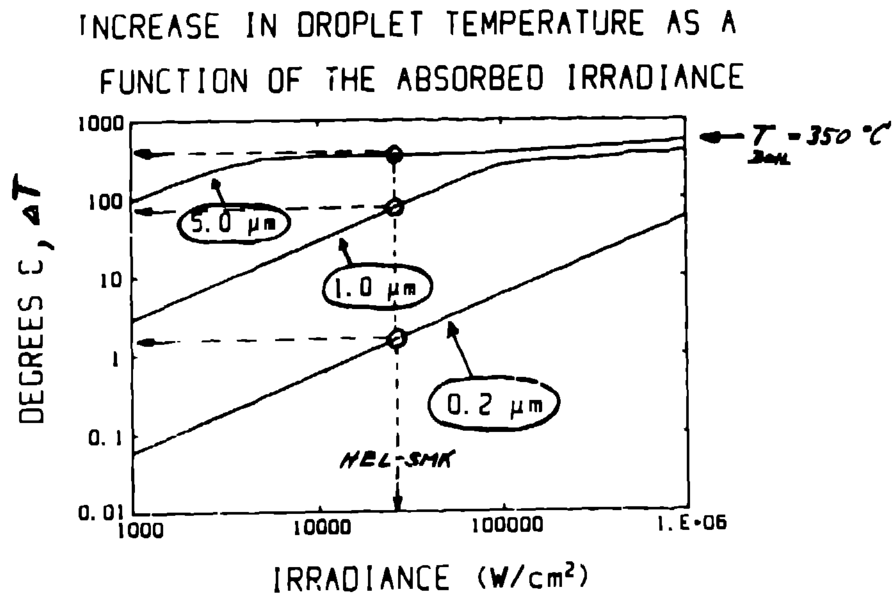

Figure 5. Temperature increase of single FO droplets of various sizes, as a function of the absorbed irradiance. Notice that a small, submicron FO droplet does not heat up very much, whereas a 5 micron FO droplet can easily heat up to boiling.

The basic point we are trying to make in this section is that small droplets of FO do not vaporize, but large particles of FO heat up to boiling and start vaporizing. Moreover, transmission measurements at 3.8µm and in the IR are consistent with an average particle size of about 0.67 µm. This explains why the FO did not vaporize, and so blocked the beam.

4. SOLVING THE HOT-SPOT PUZZLE.

Figure 6 shows our conception of how the hot spot developed. As shown in the previous section, large FO drops (there is a non-negligible fraction of such particles in the polydisperse distribution of FO utilized in the test) heat up by hundreds of degrees, after which they start to emit thermal radiation according to the Stefan-Boltzmann law. This thermal radiation then suffers multiple scattering in the fogoil, spreading to a distance of a few meters. This spread may be estimated by the following expression (Box and Deepak (1981)):

$$\Delta r = \sqrt{\frac{\tau}{3}}\,\frac{L}{ka} \qquad (4.1)$$

where τ is the optical depth of the smoke cloud, L is propagation distance (10m), k is the wavenumber of the IR radiation ($k = 2\pi/\lambda = 0.6(\mu m)^{-1}$ for wavelengths in the 8-12 μm region), and a is the radius of the droplet. From transmission measurements, $\tau = 1$, giving $\Delta r = 10$ m. This is in order-of-magnitude agreement with the observed thermal imager data.

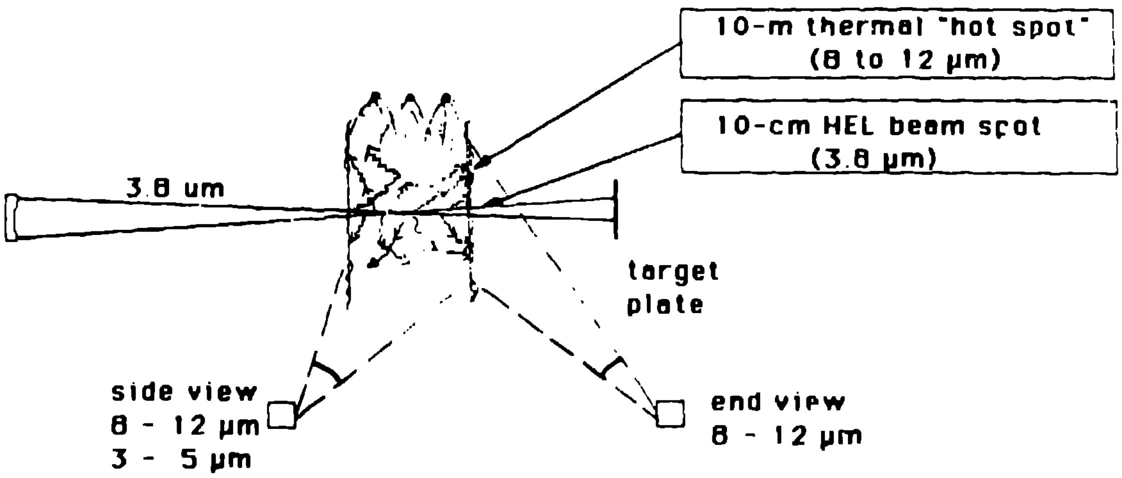

Figure 6. Schematic representation to explain the Hot-spot puzzle.

Figure 7 summarizes the physics of the FO anomaly and the observed thermal imager hotspot. Data in Fig. 7 are qualitative because no detailed size distribution measurements could be performed within the beam path before or just after the irradiation.

The last remaining problem is that such hot spots were observed in clear-air shots as well. We speculate that in this case, there were dust particles in the beam path. Dust particles (quartz) can easily heat up to 1000°K on the scale of 2 seconds, at a flux level of $10 kW/cm^2$. These hot particles will then radiate thermal energy, giving rise to the hot spot we just discussed. These hot particles are sometimes referred to as "fireflies".

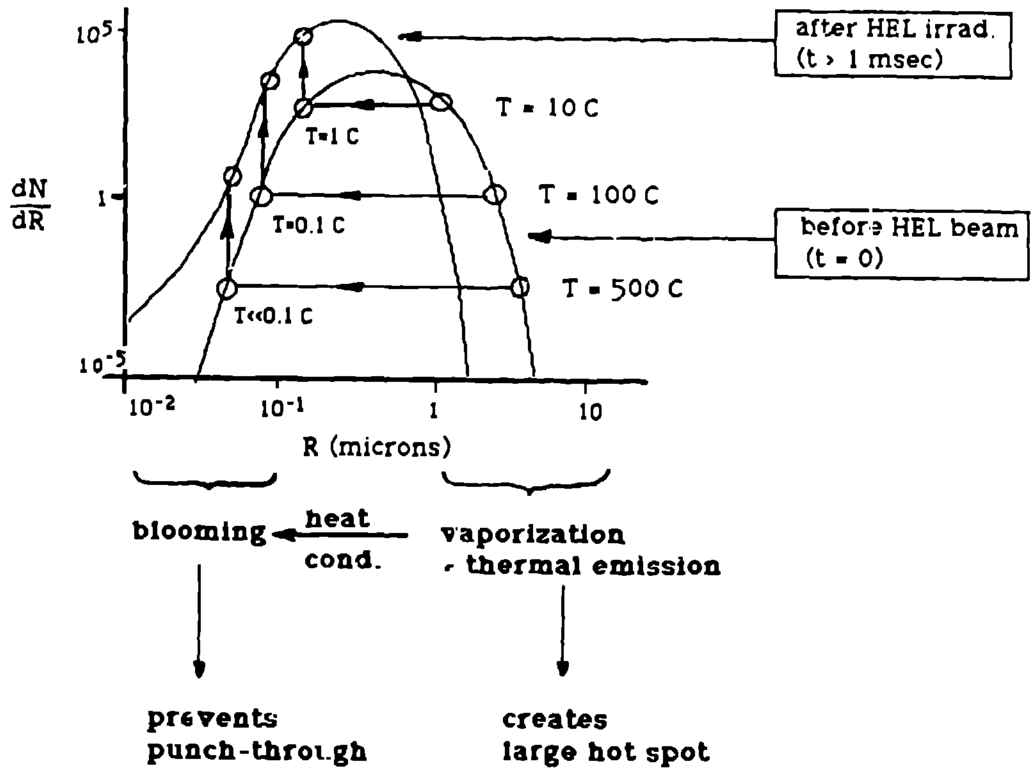

Figure 7. A qualitative depiction of the physics FO anomaly.

5. CONCLUSIONS.

We have come to two conclusions, based on our analyses of the HELSMK-I data for FO.

1) Fog-oil does not vaporize easily as white phosphorous or water might. Fog-oil enhances thermal blooming in air. HEL punch-through is prevented due to blooming. Therefore, **Fogoil is an effective shield** against HEL threat at 3.8μm for flux levels of a few kilowatts/cm^2.

2) We helped solve the hot spot puzzle, by estimating that the thermal radiation from the large-particle fraction (<< 1%) of the FO distribution can undergo multiple scattering from the FO droplets, giving rise to a large hotspot. We note that the FO hot spot could be used to diagnose the HEL source.

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